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REFERENCE-FIGURES: 1

ABSTRACT:

A method is described for catalyst-induced growth of carbon nanotubes, nanofibers, and other nanostructures on the tips of nanowires, cantilevers, conductive micro/nanometer structures, wafers and the like. The method can be used for production of carbon nanotube-anchored cantilevers that can significantly improve the performance of scaning probe microscopy (AFM, EFM etc). The invention can also be used in many other processes of micro and/or nanofabrication with carbon nanotubes/fibers. Key elements of this invention include: (1) Proper selection of a metal catalyst and programmable pulsed electrolytic deposition of the desired specific catalyst precisely at the tip of a substrate, (2) Catalyst-induced growth of carbon nanotubes/fibers at the catalyst-deposited tips, (3) Control of carbon nanotube/fiber growth pattern by manipulation of tip shape and growth conditions, and (4) Automation for mass production.

CROSS-REFERENCE TO RELATED APPLICATIONS

(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2002/0046953 A1**

Lee et al. (43) **Pub. Date: Apr. 25, 2002**

(54) **CATALYST-INDUCED GROWTH OF CARBON NANOTUBES ON TIPS OF CANTILEVERS AND NANOWIRES**

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(21) Appl. No.: **09/873,928**

(22) Filed: **Jun. 4, 2001**

Related U.S. Application Data

(63) Continuation-in-part of application No. 09/694,978, filed on Oct. 24, 2000.

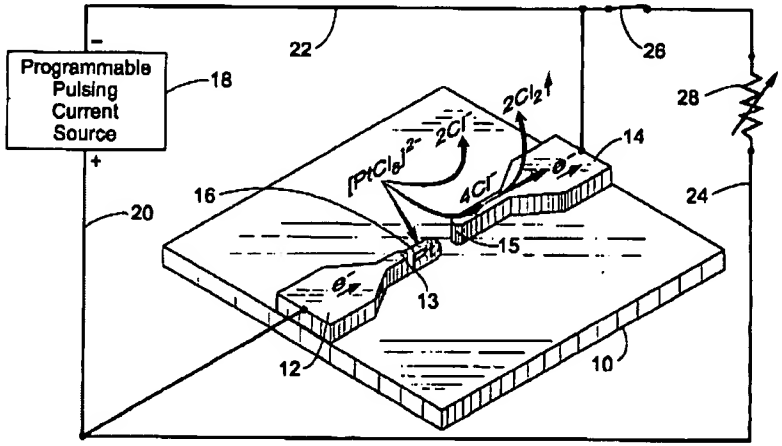
Publication Classification

(51) Int. Cl.[7] C25D 5/18; C25D 7/12; B32B 9/04

(52) U.S. Cl. 205/104; 205/192; 428/411.1; 205/157; 428/446

(57) **ABSTRACT**

A method is described for catalyst-induced growth of carbon nanotubes, nanofibers, and other nanostructures on the tips of nanowires, cantilevers, conductive micro/nanometer structures, wafers and the like. The method can be used for production of carbon nanotube-anchored cantilevers that can significantly improve the performance of scaning probe microscopy (AFM, EFM etc). The invention can also be used in many other processes of micro and/or nanofabrication with carbon nanotubes/fibers. Key elements of this invention include: (1) Proper selection of a metal catalyst and programmable pulsed electrolytic deposition of the desired specific catalyst precisely at the tip of a substrate, (2) Catalyst-induced growth of carbon nanotubes/fibers at the catalyst-deposited tips, (3) Control of carbon nanotube/fiber growth pattern by manipulation of tip shape and growth conditions, and (4) Automation for mass production.



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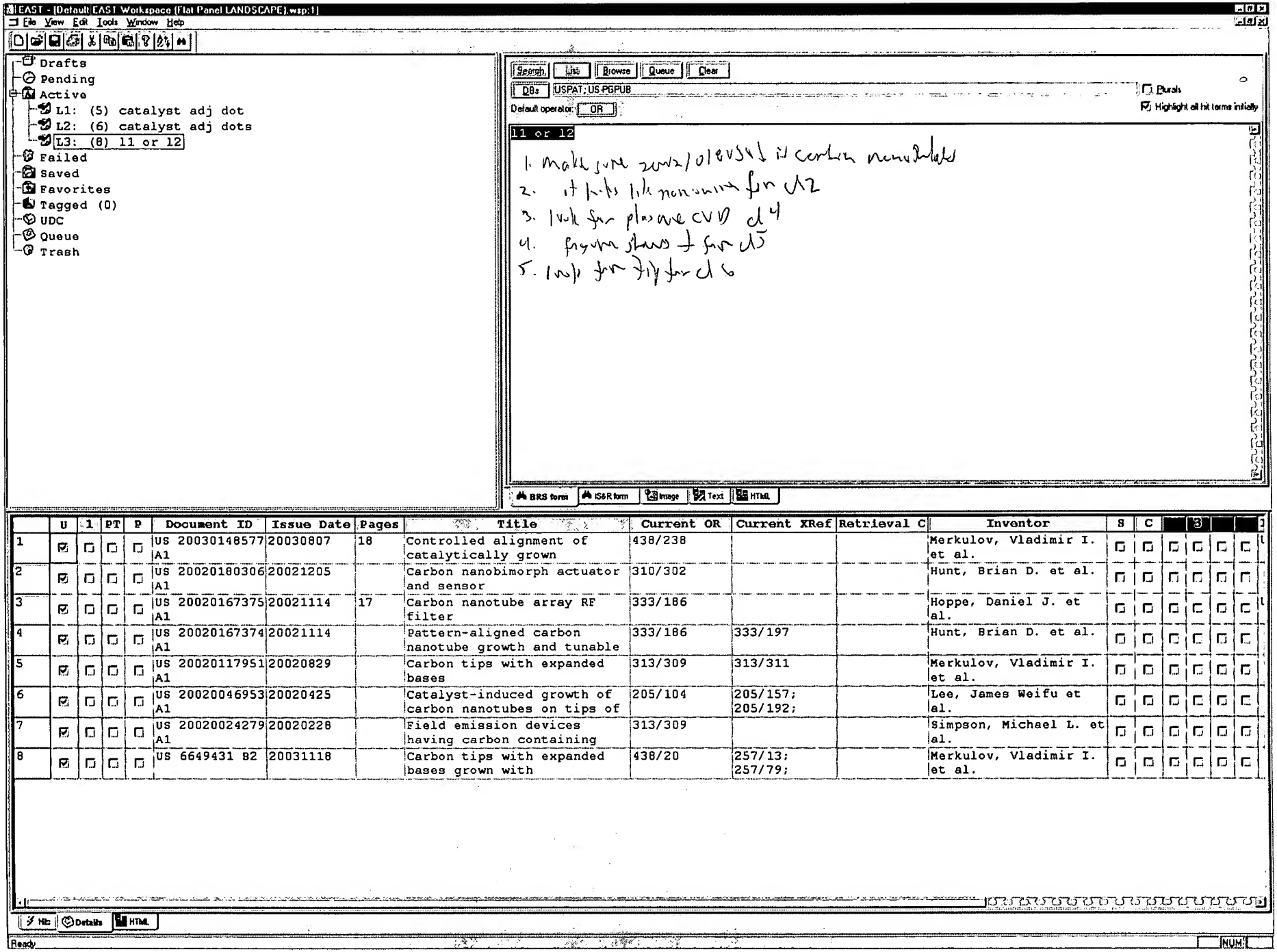

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1	☑	☐	☐	☐	US 20030148577 A1	20030807	18	Controlled alignment of catalytically grown	438/238			Merkulov, Vladimir I. et al.	☐	☐	☐
2	☑	☐	☐	☐	US 20020180306 A1	20021205		Carbon nanobimorph actuator and sensor	310/302			Hunt, Brian D. et al.	☐	☐	☐
3	☑	☐	☐	☐	US 20020167375 A1	20021114	17	Carbon nanotube array RF filter	333/186			Hoppe, Daniel J. et al.	☐	☐	☐
4	☑	☐	☐	☐	US 20020167374 A1	20021114		Pattern-aligned carbon nanotube growth and tunable	333/186	333/197		Hunt, Brian D. et al.	☐	☐	☐
5	☑	☐	☐	☐	US 20020117951 A1	20020829		Carbon tips with expanded bases	313/309	313/311		Merkulov, Vladimir I. et al.	☐	☐	☐
6	☑	☐	☐	☐	US 20020046953 A1	20020425		Catalyst-induced growth of carbon nanotubes on tips of	205/104	205/157; 205/192;		Lee, James Weifu et al.	☐	☐	☐
7	☑	☐	☐	☐	US 20020024279 A1	20020228		Field emission devices having carbon containing	313/309			Simpson, Michael L. et al.	☐	☐	☐
8	☑	☐	☐	☐	US 6649431 B2	20031118		Carbon tips with expanded bases grown with	438/20	257/13; 257/79;		Merkulov, Vladimir I. et al.	☐	☐	☐

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5	US 20020167374 A	21						☑					US-PG
6	US 20020117951 A	12						☑					US-PG
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made using the actuation methods previously discussed in the nanobimorph actuator section: piezoelectric, light, or electrostatic.

[0021] In yet another embodiment, the invention is directed to mechanical signal processing systems utilizing the nanobimorph actuators and oscillators of the current invention. For example, in one embodiment, actuators can be used to produce switches and mechanical transistors, while in another embodiment oscillator arrays containing elements with controllably varying resonant frequencies form the basis for high-speed Fourier signal processing.

[0022] In still yet another embodiment the nanotubes comprising the nanobimorph self-assemble into the nanobimorph having a specified diameter and height suitable for use in the devices of the current invention.

[0023] In still yet another embodiment, the substrate is made of a semiconductor such as, for example, oxidized silicon or aluminum oxide, coated with a metal catalyst film such as, for example, Ni or Co. In this embodiment, the silicon can be further doped to adjust the electronic properties of the substrate surface.

[0024] In still yet another embodiment, the nanotubes comprising the nanobimorph are self-assembled from an inert material such as, for example, carbon utilizing a carbon feedstock gas such as, for example, ethylene.

[0025] In still yet another embodiment, the invention is directed to a system for the detection of substances comprising multiple detectors as described above, such that parallel processing of molecules can be carried out.

[0026] In still yet another embodiment, the invention is directed to growth and processing techniques to control nanobimorph location and orientation; and methods for positioning nanotubes during growth, including nanoscale patterning of catalyst dots to seed the growth of vertical nanotubes on integrated electrodes.

DRAWING DESCRIPTION:

BRIEF DESCRIPTION OF THE DRAWINGS

[0027] These and other features and advantages of the present invention will be better understood by reference to the following detailed description when considered in conjunction with the accompanying drawings wherein:

[0028] FIG. 1 is a schematic view of an embodiment of a nanobimorph according to the invention.

[0029] FIG. 2 is a schematic view of an embodiment of a nanobimorph in operation as an actuator or oscillator according to the invention.

[0030] FIG. 3 is a schematic view of an embodiment of a nanobimorph in operation as a sensor according to the invention.

[0031] FIG. 4a is a schematic view of an embodiment of a process for forming a nanobimorph according to the invention.

[0032] FIG. 4b is a schematic view of an embodiment of a process for forming a nanobimorph according to the invention.

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Hunt et al. (43) **Pub. Date: Dec. 5, 2002**

(54) **CARBON NANOBIMORPH ACTUATOR AND SENSOR**

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(21) Appl. No.: **10/052,302**

(22) Filed: **Jan. 18, 2002**

Related U.S. Application Data

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Publication Classification

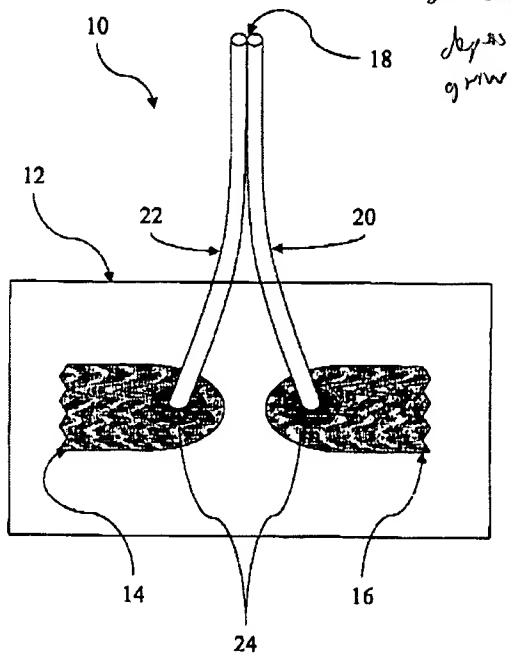
(51) Int. Cl.[7] **G21H 1/00**

(52) U.S. Cl. **310/302**

(57) **ABSTRACT**

A nanomechanical actuator/oscillator device and system are provided. The nanomechanical actuator/oscillator device comprising nanobimorphs, such as nanotubes, designed such that inducing a difference in charge density between the tubes (e.g. by biasing one tube positive with respect to the other with sufficient tube-to-tube contact resistance) induces lateral movement in the end of the bimorph, forming a nanoscale resonator, as well as a force sensor when operated in an inverse mode. A method of producing a novel nanobimorph structure with integrated electrodes is also provided.

see claim 38
deposit catalyst spot
grow nanostructure



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5	US 20020167374 A	21						☑					US-PG
6	US 20020117951 A	12						☑					US-PG
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[0050] Accordingly, this invention is also directed to a method of forming a highly uniform carbon nanotube array. Prof. Jimmy Xu at Brown University, has developed a nanopore-template technology for fabrication of dense nanotube arrays with better than 5% diameter uniformity. The uniformity of this Si-compatible process is far superior to that achieved in other approaches to nanotube array fabrication, and exceeds the perfection of conventional high resolution lithographic techniques at the size scale of interest here (10-30 nm diameters). Although only vertically arranged arrays of nanotubes are discussed below, other novel array fabrication techniques may also prove suitable for production of uniform nanotube arrays for the proposed RF filter device. A basic advantage of the vertically aligned array structure is that the vertically-oriented resonator geometry provides a highly area-efficient means of packing the nanotube oscillators, in contrast to membrane or in-plane resonator structures. It should also be understood that nonuniform nanotube arrays with controlled patterns of nanotube placement may be useful for more complex filtering and signal processing applications. Such controlled nonuniform nanotube arrays could be produced by electron beam lithography patterning of nanotube catalyst dots.

[0051] Returning to the structure of the underlying nanotube array system 10, shown in FIG. 1, it should be understood that the substrate 12 can be made of any material which can withstand the temperatures required for growth of the nanotube array 18 and which can be modified to provide a suitable nucleation point for growing the nanotube array 18 on the electrode 20 between the two waveguides 14 and 16 of the nanomechanical device 10, such as, for example, metallized Si oxide wafers, other semiconductor substrates, anodized alumina, glass, or sapphire. In turn, any suitable electrode and catalyzing metal can be used for the electrode 20 and to activate the nucleation point on the surface of the substrate 12, such as, for example, nickel or cobalt. Alternatively, the catalyzing metal could be an alloy of two or more metals such as a Co/Ni or Ti/Ni alloys. The metal catalysts could also be produced by pyrolysis of inorganic or organic metal-containing compounds, such as, for example, Ferric Nitrate or Cobalt Chloride. Accordingly, in the limit of sub-50 nm catalyst dots, it is possible to nucleate growth of a single nanotube at a catalyst location. An integrated electrode 20 can be produced by combining the catalyst dots with non-catalytic electrodes. This ability to precisely locate and orient the growth of individual nanotubes provides the basis for fabrication of the controlled geometry nanotube arrays. Such a method may utilize an electron-beam lithography system. A refinement of the catalyst dot patterning process could include pre-etched pores in a substrate or electrode to contain and confine the catalyst material. In addition, the sidewalls of such pores would serve to direct the vertical growth of nanotubes growing op out of such pores.

[0052] A possible process for forming the nanofilter array 18 of the present invention comprising utilizing a chemical vapor deposition (CVD) technique is shown schematically in FIG. 3. In a first step a substrate 12, such as, for example, silicon is coated with a high purity metal film, such as, for example, Al. The metal is then anodized in a multistep process to produce germination points or pores in a highly ordered nanopore array in the metal oxide surface, as shown in FIG. 3(a). Next, a small amount of catalytic material, such as, for example, Co or Ni is electrochemically deposited in the bottom of the pores to serve as a catalyst for carbon nanotube nano-feature 18 growth, as shown in FIG. 3(b). Finally, as shown in FIG. 3(c), the array of nanotube nano-features 18 is self-assembled by pyrolysis of a suitable feedstock, such as, for example, acetylene gas diluted in nitrogen and/or ammonia at about 650 C and the array of nanotube nano-features 18 is then partially exposed by etching the metal oxide film in a mixture of phosphoric and chromic acids. The anodized

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Hoppe et al. (43) **Pub. Date: Nov. 14, 2002**

(54) **CARBON NANOTUBE ARRAY RF FILTER**

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(21) Appl. No.: **10/113,250**

(22) Filed: **Apr. 1, 2002**

Related U.S. Application Data

(60) Provisional application No. 60/280,396, filed on Mar. 30, 2001.

Publication Classification

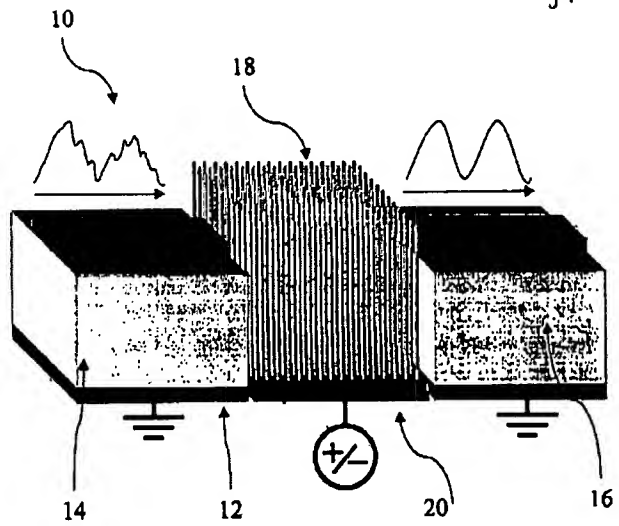
(51) Int. Cl.[7] **H03H 9/00**

(52) U.S. Cl. **333/186**

(57) **ABSTRACT**

A tunable nanomechanical resonator system comprising an array of nanofeatures, such as nanotubes, where the nanofeatures are in signal communication with means for inducing a difference in charge density in the nanofeature such that the mechanical resonant frequency of the nanofeature can be tuned, and where the nanofeature is in signal communication with a waveguide or other RF bias conduit such that an RF signal having a frequency corresponding to the mechanical resonant frequency of the array will couple to the array thereby inducing resonant motion in the array of nanofeatures, and subsequently coupling to an output waveguide, forming a nanoscale RF filter is provided. A method of producing a nanoscale RF filter structure controllably positioned and oriented with a waveguide and integrated electrodes is also provided.

d38 deposit catalyst spots
& grow nanotubes off the spots



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vibrate, as shown in FIGS. 2 and 3, and such that the resonant frequency of the vibratable portion of the nanotube is tunable.

[0056] Returning to the structure of the underlying suspended nanotube system 10, shown in FIGS. 1 to 3, it should be understood that the substrate 12 can be made of any material which can withstand the temperatures required for growth of the nanotube 24 and which can be modified to provide a suitable nucleation point for orienting and growing the nanotube 24 between the two posts 14 and 16 of the nanomechanical device 10, such as, for example, metallized Si oxide wafers, alumina, or sapphire. In turn, any suitable electrode and catalyzing metal can be used for the electrodes 18 and 20 and to activate the nucleation point 17 on the surface of the substrate 12, such as, for example, nickel or cobalt. Alternatively, the catalyzing metal could be an alloy of two or more metals such as a Co/Ni or Ti/Ni alloy. The metal catalysts could also be produced by pyrolysis of inorganic or organic metal-containing compounds, such as, for example, Ferric Nitrate or Cobalt Chloride. Accordingly, in the limit of sub-50 nm catalyst dots, it is possible to nucleate growth of a single nanotube 24 at a catalyst location. Integrated electrodes 18 and 20 can be produced by combining the catalyst dots with non-catalytic electrodes. This ability to precisely locate and orient the growth of an individual nanotube and make electrical contact to the two ends of the tube provides the basis for fabrication of the suspended nanotube oscillator structure. Such a method may utilize an electron-beam lithography system.

[0057] This patent is also directed to a novel "pattern-aligned" growth process for orienting the growth of the nanotube between the posts. Two alternative processes for forming the nanomechanical device of the present invention comprising a suspended nanotube resonator utilizing a chemical vapor deposition (CVD) technique are shown schematically in FIGS. 5 to 7. In a first method, as shown in FIGS. 5 to 7, the in-plane nanotube growth is controlled by pre-patterning nanotube alignment structures into Si or Si-on-Insulator (SOI) wafers.

[0058] The basic technique to construct the alignment structures, such as the in-plane pointed silicon cantilevers shown in FIG. 1, uses standard semiconductor processing methods to construct a protruding cantilever from an undercut SOI layer on a Si substrate. To ensure proper growth the region of the cantilevers is coated with a thin catalyst film such as Ni, Co, or other metal-based mixtures or compounds to locally nucleate nanotube growth. The entire material is capped with a refractory metal such as sputter Nb for protection.

[0059] As shown in one basic embodiment, (FIG. 5), a trilayer Si/SOI/Nb starting material is deposited utilizing a standard CVD method. A catalyst layer may be sputtered on top of the SOI layer at this point in either an undifferentiated layer followed by a liftoff step to pattern the catalyst (Step A); or the catalyst may be deposited in a pattern prior to the deposition of the cap layer using a suitable controlled method, such as BCP, photolithographic/ebeam, or annealing (Step B). The trilayer is then etched via a suitable etching technique (an RIE or wet etch for the Nb; a wet or dry etch for the catalyst; a dry or HF etch for the SOI) to define the post, or electrodes. (Step C) Once the necessary support structures are constructed, the nanotubes are grown via self-assembly to bridge the gap between the two supports. (Step D). A process similar to this is described in detail in a paper by Han et al., J Appl. Phys. 90(11), 5731 (2001), which is incorporated herein by reference.

[0060] Although one method of forming the electrode supports is described

(19) **United States**

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Hunt et al. (43) **Pub. Date: Nov. 14, 2002**

(54) **PATTERN-ALIGNED CARBON NANOTUBE GROWTH AND TUNABLE RESONATOR APPARATUS**

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(21) Appl. No.: **10/113,247**

(22) Filed: **Apr. 1, 2002**

Related U.S. Application Data

(60) Provisional application No. 60/280,597, filed on Mar. 30, 2001. Provisional application No. 60/280,591, filed on Mar. 30, 2001.

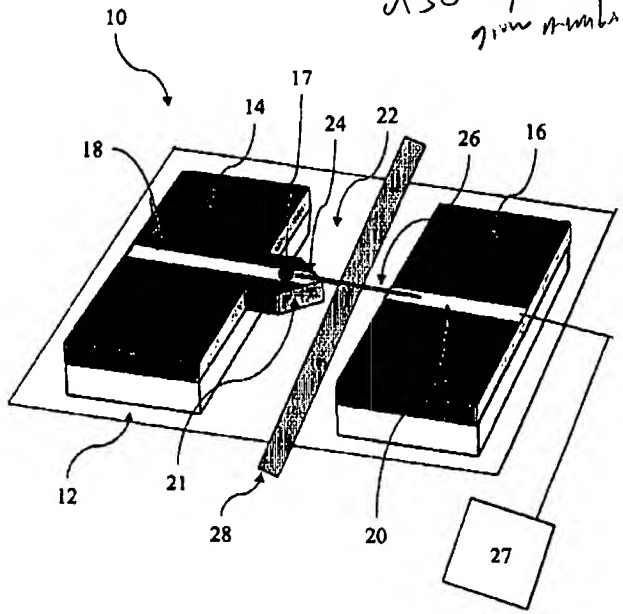
Publication Classification

(51) Int. Cl.[7] H03H 9/00

(52) U.S. Cl. 333/186; 333/197

(57) **ABSTRACT**

A tunable nanomechanical oscillator device and system is provided. The nanomechanical oscillator device comprising at least one nanoresonator, such as a suspended nanotube, designed such that injecting charge density into the tube (e.g. by applying a capacitively-coupled voltage bias) changes the resonant frequency of the nanotube, and where exposing the resonator to an RF bias induces oscillitory movement in the suspended portion of the nanotube, forming a nanoscale resonator, as well as a force sensor when operated in an inverse mode. A method of producing an oriented nanoscale resonator structure with integrated electrodes is also provided.



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[0024] The method can include two main steps: formation of a precisely placed single metal catalyst dot on a substrate by utilizing EBL in conjunction with electron-gun metal evaporation; and catalytic growth of a NCCCT on the substrate using PE-CVD.

[0025] Growth of CNTs and CNFs requires the presence of a catalytic precursor. Ni can be used as a catalyst. However, other metals such as Fe, Co, etc. can also be utilized as the catalyst with these procedures, the results being similar.

[0026] In order to grow a single carbon nanocone (CNC) or CNF, formation of a single catalyst nanoparticle (or cluster) may be required. This catalyst nanoparticle is formed by forming a metal catalyst dot with width (diameter) D, and film thickness, T. FIGS. 1A-1F show fabrication of vertically aligned carbon nanofibers (VACNFs) utilizing plasma enhanced chemical vapor deposition (FIGS. 1E-1F) preceded by electron-beam lithography and metal evaporation (FIGS. 1A-1D). A catalyst dot 150 is fabricated on a substrate using electron beam (e-beam) lithography and electron gun (e-gun) metal evaporation as shown in FIGS. 1A-1D. A substrate 110 is first coated with an e-beam resist 120 (e.g. PMMA); the resist 120 is then e-beam exposed and developed (FIGS. 1A and 1B), to produce a small opening 130 in the resist 120 with width (diameter) D. A buffer layer 140 (Ti in this case) is deposited next to prevent the formation of catalyst silicide and to impede catalyst diffusion at elevated temperatures. Next, a catalyst layer 150 (Ni, in this case) is deposited (FIG. 1C). Finally, a single, isolated catalyst dot is obtained by lifting off the metal-coated resist in acetone (FIG. 1D). Multiple dots, or pattern arrays of dots, also can be produced by this process.

[0027] FIGS. 1E-1F show a VACNF is prepared by PECVD in a vacuum chamber 160. The vacuum chamber 160 can include an anode 162 and a cathode 164. The cathode 164 can also function as a heater. One of the advantages of this method is that high vacuum is not required, i.e. the chamber 160 can be evacuated using only a mechanical pump (FIGS. 1E and 1F). Upon ammonia plasma pre-etching (alternatively, hydrogen and other gases can be used) and annealing the Ni/Ti assembly on Si at the elevated temperatures required to grow VACNFs (.about.700.degree. C. in this case), the Ti layer 140 continues to adhere to the Si substrate 110, whereas the initially continuous Ni layer 150 breaks into one or more little nanoparticle droplets (FIG. 1E).

[0028] FIGS. 2A-2D show scanning electron microscopy images of single and multiple vertically aligned carbon nanofibers formed from a single or multiple catalyst dot. Upon heating and ammonia plasma pre-etching the catalyst layer breaks into nanodroplets. Each nanodroplet provides for catalytic growth of an individual nanofiber. This droplet is the necessary precursor for the catalytic growth of a single VACNF at this predetermined location. Within an initially large dot, multiple droplets are formed (FIG. 2A). See FIG. 2B also. However, below a critical dot size only a single nanoscale Ni droplet forms (FIG. 2B) and consequently only a single nanofiber is grown. See FIG. 2D also. The critical dot size, and the size of its resulting Ni droplet, will depend upon the choice of the buffer layer between the catalyst and the substrate, the type and thickness of the catalyst used, and the annealing/growth temperature. For example, for growth of a single VACNF at 700.degree. C. using an initially 15 nm thick Ni catalyst on a Ti buffer layer on Si, the critical dot size (diameter) is .about.350 nm. The diameter of the Ni nanoparticle droplet formed is about a factor of 3 smaller, .about.100 nm in this example. Smaller catalyst nanoparticles can be obtained by initially forming a smaller catalyst dot. For instance, 100 nm dots with a 10 nm thick Ni layer produce Ni droplet

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Merkulov et al. (43) **Pub. Date: Aug. 29, 2002**

(54) **CARBON TIPS WITH EXPANDED BASES**

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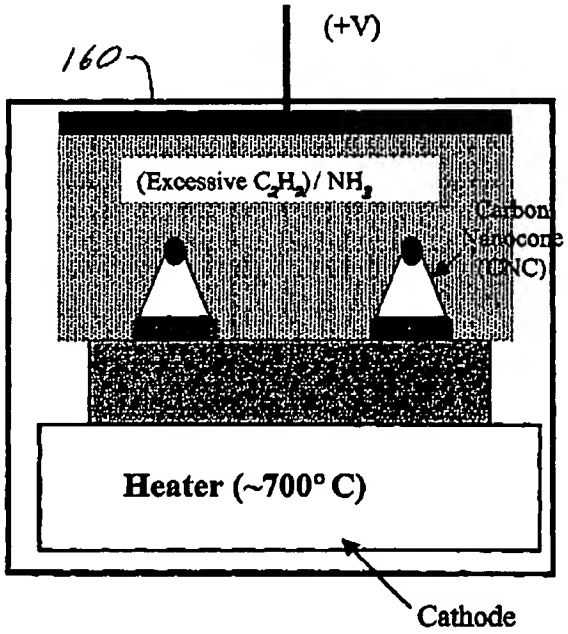
(57) **ABSTRACT**

Systems and methods are described for carbon tips with expanded bases. A method includes producing an expanded based carbon containing tip including: fabricating a carbon containing expanded base on a substrate; and then fabricating a carbon containing fiber on the expanded base. An apparatus includes a carbon containing expanded base coupled to a substrate; and a carbon containing fiber coupled to said carbon containing expanded base.



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[0032] The invention can include catalytically-controlled growth of vertically aligned (i.e. substantially perpendicular to the substrate surface), multi-walled CNTs (Merkulov et al., 2000). Referring to FIG. 2, a PE-CVD process for growing MWNT in place in a prefabricated electrode structure is depicted. A vacuum chamber 200 includes an anode 210 and a cathode 220. A substrate 230 is located on the cathode 220. A barrier layer 235 is formed on the substrate 230. A plurality of dielectric layers 240 alternating with a plurality of extractor layers 245 compose an electrode structure 250. The process utilizes plasma-enhanced chemical vapor deposition (PE-CVD) in conjunction with evaporation and precise placement of a metal-catalyst dot 255. The catalyst dot 255 can be a nickel catalyst particle that is deterministically placed by lithographic definition. A mixture of acetylene (C.sub.2H.sub.2) and ammonia (NH.sub.3) is used as a source gas during the PE-CVD process. The substrate 230 is heated above .about.600.degree. C. After the plasma is turned on, MWNTs grow selectively at the locations where catalyst dots (e.g., Ni, Fe, Co) were pre-deposited. A single self-aligned MWNT 260 can be grown in place (in situ) via the catalyst dot 255. The MWNT 260 can be carbon containing or substantially pure carbon. The method depicted in FIG. 2 can also be used to fabricate self-aligned single wall carbon containing nanotube and./or self-aligned carbon containing nanofibers. Similarly, these SWNTs and/or NFs can be carbon containing or substantially pure carbon.

[0033] In the method depicted in FIG. 2, no hot filament is present and the substrate 230 is heated directly by placing them on a heater plate (e.g., the cathode 220). This technique has the advantages of growth-temperature control and large-area deposition (not possible with a hot filament) and therefore creates the possibility of industrial-scaleable device fabrication.

[0034] FIGS. 3A-3G show a fabrication process for a MWNT-based vacuum nanoelectronic device. The device depicted in FIGS. 3A-3G is a simple gated electron emitter structure that can be the basis for more complex vacuum nanoelectronic devices. In FIGS. 3A-3F, an electrode structure is defined through lithographic steps. In FIG. 3A, a buffer layer 305 is deposited on a substrate 300. The substrate 300 can be 4" n-Si and the buffer layer 305 can be a titanium-tungsten alloy. In FIG. 3B, alignment mark 310 are formed on the buffer layer 305. The alignment marks 310 can include gold and could be conductive traces. The alignment marks are for subsequent photolithography and critical dimension (CD) measurements. Referring to FIG. 3C, one of the steps in this process is the definition of a catalyst particle 320. The catalyst particle can include one, or more, of nickel, iron and cobalt. The catalyst can be a round dot of approximately 100 nm diameter on a 50 micron pitch. The catalyst particle can be one member of an array where the dots are arranged on a pitch of approximately 50 microns. FIG. 3D shows a dielectric layer 330 deposited over the catalyst particle 320, the traces 310 and the buffer layer 305. The dielectric layer can include silica. In this case, the silica can be deposited using PECVD at a temperature of approximately 275.degree. C. FIG. 3E shows an extractor layer 340 deposited over the dielectric layer 330. The extractor layer 340 can be termed a gate electrode. The extractor layer 340 can be a chromium layer approximately 150 nm thick. There is an extractor aperture 345 formed in the extractor layer 340. The extractor aperture 345 can be formed using a spin-on photoresist. FIG. 3F shows a dielectric well 350 formed in the dielectric layer 330. The dielectric well can be formed using reactive ion etching using the extractor layer 340 as an etch mask. The formation of the dielectric well should uncover the catalyst particle 320 to catalyze growth. The dielectric well 350 can be coincident with the extractor aperture 345. Referring to FIG. 3G, after the entire electrode structure is fabricated, and the catalyst is uncovered, a MWNT 360 is grown in place (in situ) within the electrode structure. The growth can be by PECVD at a

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(54) **FIELD EMISSION DEVICES HAVING CARBON CONTAINING TIPS**

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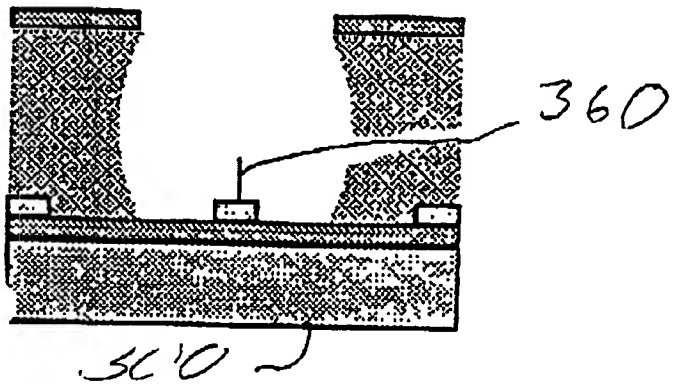
(57) **ABSTRACT**

Systems and methods are described for field emission devices having carbon nanofiber emitters. A method, includes: providing a substrate; depositing a catalyst, the catalyst coupled to the substrate; depositing a dielectric layer, the dielectric layer coupled to the substrate; depositing an extractor layer, the extractor layer coupled to the dielectric layer; forming an extractor aperture in the extractor layer; forming a dielectric well in the dielectric layer to uncover at least a portion of the catalyst; and then fabricating a carbon containing tip i) having a base located substantially at the bottom of the dielectric well and ii) extending substantially away from the substrate. An apparatus, includes: a substrate; an electrode structure coupled to the substrate, the electrode structure including a dielectric layer coupled to the substrate, the dielectric layer including a dielectric well that is formed in the dielectric layer after the dielectric layer is deposited; and an extractor layer coupled to the dielectric layer, the extractor layer including an extractor aperture; and a carbon containing tip coupled to the substrate, the carbon containing tip having a base located substantially at a bottom of the dielectric well and extending substantially away from the substrate, the carbon containing tip being grown from the bottom of the dielectric well using a catalyst that is introduced at the bottom of the dielectric well after the dielectric well is formed. A method, includes: providing a substrate on a heater plate in a vacuum chamber; providing a carbon source gas and an etchant gas; heating the substrate with the heater plate; and then fabricating a carbon tip on the substrate with the carbon source gas and the etchant gas using plasma enhanced chemical vapor.



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